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DISTRIBUTED MECHANICAL ACTUATORS FOR DESIGN OF A CLOSED-LOOP FLOW-CONTROL SYSTEM (Postprint)

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14. ABSTRACT
This report was developed under a SBIR contract.

Active flow control experiments were conducted on a two-dimensional, single-element NACA 4312 airfoil to assess the performance of vortex generators and gurney flaps as lift-enhancing devices for the control of longitudinal dynamics of an air vehicle. The vortex-generators are shown to delay boundary layer separation and provide an increase in the lift coefficient for angles of attack above 12 deg, and the gurney flaps yield a constant shift in the lift curve for all angles of attack up to stall angle. The vortex-generators are most effective when used between 2 to 5% chord, and the gurney flap is most effective when used at the trailing-edge. Experiments from actuators distributed spanwise along the wing reveal that there is minimal interaction between individual gurney flaps at low-to-moderate angles of attack, while, the interactions between the individual vortex-generators are slightly more pronounced at high angles of attack. The effects of these individual actuators can be combined linearly to produce a desired net effect.

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Distributed Mechanical Actuators for Design of a Closed-Loop Flow-Control System

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Active flow control experiments were conducted on a two-dimensional, single-element NACA 4312 airfoil to assess the performance of vortex generators and gurney flaps as lift-enhancing devices for the control of longitudinal dynamics of an air vehicle. The effort is aimed at creating a database of flow-induced effects for the design of a modular feedback control system to be used on an air vehicle technology demonstrator. Lift and drag forces are measured to quantify the effect of flow-control as a function of several actuator parameters. The vortex-generators are shown to delay boundary layer separation and provide an increase in the lift coefficient for angles of attack above 12 deg, and the gurney flaps yield a constant shift in the lift curve for all angles of attack up to stall angle. The vortex-generators are most effective when used between 2 to 5% chord, and the gurney flap is most effective when used at the trailing-edge. Experiments from actuators distributed spanwise along the wing reveal that there is minimal interaction between individual gurney flaps at low-to-moderate angles of attack, while, the interactions between the individual vortex-generators are slightly more pronounced at high angles of attack. The effects of these individual actuators can be combined linearly to produce a desired net effect. A flow-control system employing both leading-edge vortex generators and trailing-edge gurney flaps can produce significant control authority over an extended flight envelope for maneuvering air vehicles without the use of conventional control surfaces.

Nomenclature

α	angle of attack
b	airfoil span
c	airfoil chord
C_D	drag coefficient
C_L	lift coefficient
d	distance from airfoil trailing-edge
h	height of Gurney flap
w	width of Gurney flap
Re_c	Reynolds number based on mean chord and free-stream velocity
U_∞	free-stream velocity, m/s
x	distance from airfoil leading-edge
y	distance from airfoil root

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I. Introduction

Flow-control has been a subject of intensive research since the introduction of boundary-layer theory by Prandtl in 1904. Spurred by the technological breakthroughs in recent years in the areas of microelectromechanical systems, materials and advanced controls, the concept of using flow-control for controlling air vehicles without the use of conventional (movable) control surfaces now appears to be attainable. From the controls standpoint, however, the utilization of flow-control actuators introduce highly nonlinear dynamics into the flow system ("plant"), and the design of an effective controller becomes a major technical challenge. Traditional linear approaches fall far short of meeting the required demands for performance robustness and stability that enable effective implementation of these flow-control actuators. Classical robust control schemes can also lead to excessive control effort, lack of sensitivity, and may ultimately require more control authority that can be supplied by the actuators.[1] In fact, in the presence of nonsmooth phenomenon such as stall, it is unlikely that any smooth control law design technique will be effective over the entire operating envelope of an air vehicle. Therefore, in order to effectively implement a flow-control system into flight control, advanced nonlinear control schemes are necessary to accommodate many of the nonlinear effects that can occur.

An innovative modular hierarchical control architecture for implementing an active flow-control system onto aircraft flight control was recently reported by Patel *et al.*[2] The control architecture is classified into two levels; 1) a local, minor loop feedback controller, composed of Intelligent Control Modules (ICMs) that control the amount of lift created by a discrete airfoil section, and 2) a coordinating, major feedback loop controller, composed of a Global Control System (GCS) that provides coordination of ICMs in order to modulate the net pitch and roll moments created by an entire airfoil. Each individual ICM is a distinct control unit with dynamic pressure sensors, one of more actuator pairs, and a controller to regulate the lift generation of the corresponding aerostructure section. The control system architecture is not predicated upon the use of any specific design methodology for the construction of either the ICMs or the GCS, rather, provides a framework within which a control system designer may independently construct ICM control laws and a coordinating GCS using the methodologies that are most appropriate to their specific application.

In prior work,[2] we utilized this approach with suction control implemented on an airfoil section via a series of holes located upstream of the flow separation region near the trailing-edge. Self Tuning Regulators[1] were used to modulate lift over distinct wing sections which were then coordinated via a feedforward GCS. The GCS modulated the net force and center of pressure location by varying the weighting or influence coefficients of predetermined lift distributions along the airfoil span, as shown in Fig. 1. The fundamental concept underlying the present approach is the use of nonlinear controllers to address the system's inherent nonlinearity while allowing coordination of individual discrete actuator systems and their associated controllers to be coordinated by a simple linear control system. The present work seeks to extend the development of the hierarchical controller[2] in several ways.

First, instead of assuming a linear time-varying model to account for the transient behavior of the fluid flow, wind tunnel experiments are conducted to capture the spanwise and chordwise interactions of the flow control devices for extraction of empirically-based low-order physical models and input/output maps for the control system design. These physical models will replace the linear time-varying model used earlier and will better capture the relevant physics and accommodate model uncertainty. Second, two types of mechanical flow control devices—leading-edge vortex generators (LEVGs) and trailing-edge gurney flaps (TEGFs)—are used to increase the operational envelope and the controllable (aerodynamic) domain over the wing from 0 deg to post-stall angles of attack. This will lead to an overall increase in the airfoil performance using flow-control. The crucial concept underlying our design philosophy is to develop a flow-control system that incorporates multiple actuators to maximize the vehicle's performance, whereby the coordination of actuators is dictated by the GCS as per the operating conditions. The control system will layer a linear (optimal) control system over a set of nonlinear, adaptive control systems, each of which regulate the performance of a discrete actuator system for controlling the flow in a localized region of an aerodynamic surface. Once the effects of flow control actuators are fully modeled, the flow-control system will be integrated with the flight control system of a small unmanned air vehicle (UAV) for hingeless flight demonstration.

The details of the complete effort which include wind tunnel experiments for actuator characterization, system identification, design of low-order physical models, and control system validation, are beyond the scope of the present paper. In this paper, we present results from the wind tunnel tests conducted to investigate the potential of two types of (distributed) flow-control devices, LEVGs and TEGFs, that employ fundamentally different control mechanisms to affect the longitudinal dynamics of a two-dimensional NACA

4312 airfoil. Vortex generators delay/control flow separation by energizing the boundary layer through enhanced momentum mixing,[3–8] and a gurney flap affects the lift and circulation around the wing.[9–12] Both devices have been extensively researched for their lift-enhancing capabilities. Vortex generators have been traditionally used near the leading-edge of an airfoil as it is most effective in controlling flow separation and wing stall that occur at high angles of attack, and a gurney flap is used near the trailing-edge as it is most effective in affecting circulation at low to moderate angles of attack. The effectiveness of each device is significantly reduced if used outside its performance envelope. Therefore, in order to achieve control of longitudinal dynamics of an airfoil during its entire operational envelope, a combined use of these devices offer a logical alternative. An approach on the combined use of vortex generators and a gurney flap on a NACA 4412 airfoil was first reported by Storms and Jang.[13]

In our tests, both the devices (LEVGs and TEGFs) were tested for their useful ranges of applicability on a NACA 4312 airfoil at low Reynolds numbers. Parametric studies were conducted using passive devices to determine optimal settings of the actuators in order to maximize their effectiveness and minimize their interactions. One of the key objectives of the parametric study was to identify proper positioning of devices to minimize (ideally eliminate) interactions between actuators for the construction of independent, local flow-control systems. While positioning the devices in this manner will eliminate potential synergies between multiple flow-control devices, it will greatly simplify the analysis of the relevant physics and reduce the complexity of the initial control system design. Future implementations of this approach are envisioned that do not require this isolation of flow-control actuators, a simplified system where the interactions are handled physically (that is, by physically separating the flow-control actuators sufficiently to isolate their regions of influence) provides a valuable precursor implementation and provides a firm foundation for the development of more complete models and their associated control systems.

II. Experimental Setup

The airfoil used in this study is a two-dimensional NACA 4312 with 24.76 cm (9.75 in) constant chord and 60.96 cm (9.75 in) span dimensions, shown in Fig. 2. The experiments were conducted in a 0.91 m $\times$ 0.91 m closed-return subsonic wind tunnel at the University of Toledo. The flow in this tunnel is driven by a 5 ft diameter, 14-blade, variable-pitch fan coupled to a 150-hp electric motor that allows for speeds over 90 m/s in the test section. The tunnel is equipped with an electric motor which was used to change the model positioning, providing an accuracy of ± 0.5 deg for the angle of attack. The flow in the test section was uniform with a turbulence level of 0.2% outside of wall boundary layers. The tests were performed at a chord Reynolds numbers, Re_c, of 2.6×10^5 and 3.15×10^5(corresponding Mach numbers of 0.045 and 0.05), based on the airfoil chord and freestream velocities, U_∞, of 15.17 m/s and 17.97 m/s, respectively. Angles of attack ranging from -10 to 24 deg with 2 deg increments were examined. Lift and drag measurements were taken using a four-component force balance. The data acquisition system provided good repeatability as 500 samples were taken over a period of 15 seconds at each data point.

Counter-rotating pairs of leading-edge vortex-generators (LEVGs), as shown in Fig. 3, were tested at different chord locations of x/c = 0.02, 0.027, 0.035, 0.047, 0.07, and 0.095. The LEVGs were mounted parallel to the leading-edge, centered across the airfoil span, and were evenly spaced with a distance of 2 cm between each pair. The separating distance between the VGs in a single pair was 1 cm. All VGs were inclined at an angle of 20° deg with respect to the free-stream flow. Tests were conducted to investigate the effect of LEVGs for different chord locations, the number of pairs used at a given chord location (2.8% c), and when used discretely between spanwise distances of y/b = 0–0.25, 0.25–0.5, 0.5–0.75, and 0.75–1. The first series of gurney flap experiments consisted of a single trailing-edge gurney flap (TEGF) tested at different heights (h/c = 0.009, 0.028, 0.09, 0.01, 0.02, and 0.05) and locations near the trailing-edge (d/c = 0, 0.002, 0.004, 0.008, 0.012, and 0.016). Note d is measured from the airfoil trailing-edge. The TEGF was mounted on the windward side of the airfoil across 45% of the airfoil span, centered at the airfoil center-span (y/b = 0.5), as shown in Fig. 4. After the initial tests of a single TEGF were completed, tests were conducted to investigate the effects of distributed TEGFs, as illustrated in Fig. 5.

III. Results and Discussion

A. Effect of Leading-Edge Vortex Generators

The variation of the lift coefficient C_L and drag coefficient C_D as a function of angle of attack (α = -5 to 26 deg) and chord location for the leading-edge vortex generators (LEVGs, hereafter VGs) is shown in Fig. 6. It can be seen in Fig. 6a that the VGs produce a significant lift increment compared to the baseline configuration, and the effects are different for different chord locations. The effects on the lift are most pronounced for the VGs located between 2 to 7% chord. The drag data (see Fig. 6b) shows that there is a significant (parasitic) drag penalty associated with the VGs for all cases examined. A moderate 10% increase in the maximum lift coefficient is observed for the most effective VG configuration. A corresponding delay in flow separation from α = 14 to 22 deg is also observed. These results reflect similar trends as those reported in earlier studies.[8,13] The NACA 4312 airfoil is believed to suffer from a trailing-edge stall progression, similar to a NACA 4412 airfoil,[14] which explains the shift in the VG effectiveness as a function of chord location. The effects of a VG are sensitive to the condition of flow separation at that location, and therefore, at moderate to high angles of attack, as the flow separation point moves closer to the leading-edge, the effects of the VGs between 2 to 5% chord are much stronger than the VGs located at 9.5% chord (in the fully separated flowfield). For all VG cases examined, it was found that the lift-to-drag ratio was reduced due to a large rise in the drag. Therefore, for practical applications, smart/deployable VGs[15] should be implemented so they can be stowed during cruise conditions.

Additional tests were conducted to investigate the linearity of combined VG pairs. Specifically, the relationship between the location of the actuator pairs and the effect of increasing the number of VG pairs on the lift produced was investigated. Figures 7 and 8 highlight the results from these tests. It is shown in Fig. 7a that the effect of VGs is similar regardless of their spanwise location for angles of attack up to 16 deg. For $\alpha > 16$ deg, the changes in the effect are more pronounced. As no end-plates were used on the NACA 4312 airfoil during the wind tunnel tests, at high angles of attack, due to the presence of strong three-dimensional flows near the wing tip, the effect of VGs located between y/b = 0.75–1 is different than other cases. Additional experiments were conducted at α = 22 and 26 deg as these angles yielded the most pronounced effects for the VGs and therefore present ideal test cases. For these tests, the VGs were placed at 2.8% chord from the leading-edge. It is observed in Fig. 8a that there is a slight effect due to spanwise VG placement. As aforementioned, this is a reflection of the different end conditions enforced in the wind tunnel. These end effects, however, are not as prominent as increasing the number of VGs as shown in Fig. 8b, which shows that as the number of VG pairs is increased, the lift coefficient increases linearly.

B. Effect of Trailing-Edge Gurney Flaps

The variation of the lift and drag coefficients for the trailing-edge gurney flaps (TEGFs, hereafter GFs) as a function of flap height is shown in Fig. 9. Tests were conducted for α = -4 to 22 deg with 2 deg increment. A constant shift in the C_L versus α curve was achieved for all cases up to α = 14 deg (stall angle); see Fig. 9a. For experiments shown in Fig. 9, the use of a GF increased the lift coefficient by 60 to 25% between α = 1 to 10 deg. It was also observed that the incremental changes in the lift coefficient progressively diminished for for $\alpha > 10$ deg. The GFs of all heights tested produced increased lift coefficient, and the increment peaked between the h = 1 to 2% chord. Increasing the flap height beyond 2% chord did not yield much increase in the lift coefficient. It is believed that the effect of increasing the GF height beyond an optimum setting will progressively diminish the effect on lift coefficient. Figure 9b shows that there is a drag penalty associated with the lift increment for all GF cases examined. In the work reported by Storms and Jang[13] on a NACA 4412 airfoil, it was shown that at higher lift coefficients, the drag was reduced. They found that the maximum lift-to-drag ratio was reduced for flap heights greater than 1% chord.

A study of the efficacy of the GF relative to its proximity to the trailing-edge was also performed in the present study. Figure 10 shows the variation in lift and drag coefficients as a function of GF placement near the trailing-edge. It is evident that the most effective location for a GF is at the trailing-edge, and the effect is reduced when the GF is moved away from the trailing-edge. Figure 11a and 11c compares the effect of a GF with h = 1 and 2% chord at d = 0 on lift and drag coefficients, and Figs. 11b and 11d compare the effect of a GF with h = 2% chord for d = 0 and 8% chord (measured from the trailing-edge). It is evident that by increasing the GF height from 1% to 2%c, a considerable increase in the lift and drag coefficients was achieved for all angles of attack up to α = 16 deg. As the location of the GL was moved from d = 0 to 0.08c, a reduction in the lift and drag coefficients was observed for all α up to 16 deg. At higher angles of attack ($\alpha > 16$ deg), the flow was massively separated at the leading-edge and the effect of a GF on circulation around the airfoil was greatly diminished. The effect was further diminished as the GF is moved farther from the trailing-edge. Figure 12 shows variation in the lift and drag coefficients as a function of flap height, reiterating similar trends as observed in Figs. 11a and 11c.

As the ultimate intent of this work is to apply nonlinear control techniques to regulate phenomena local to a spanwise section, and to coordinate these regulated phenomena via a supervisory control system, the wind tunnel experiments also investigated the effects generated using a combination of distributed GFs, shown in Fig. 5. Figure 13 shows the effects of several GF combinations on the lift and drag coefficients for different angles of attack. As can be seen, increasing the number of GF sections increases both the lift and drag produced. More importantly, Fig. 14 shows that the change in lift produced varies linearly with the height and the number of GFs used. As noted previously, the VGs were most effective at high angles of attack while the GF performance was better at low angles of attack. This suggests a combination of VGs and GFs in order to maximum control authority via flow-control devices over the widest possible range of flow conditions. Accordingly, the effectiveness of this combination was studied. The lift increment from the combined use of VGs and GFs over the entire α–range examined are highlighted in Fig. 15. Figure 15a shows absolute values of the lift coefficient with and without flow-control, and Fig. 15b highlights incremental shifts in the lift coefficient to the baseline (uncontrolled) configuration. It is shown that significant control authority can be achieved using a combined flow-control system of vortex generators and trailing-edge flaps, which can be effectively use for control of longitudinal dynamics of an airfoil.

IV. Conclusions

The effectiveness of two types of flow-control actuators (leading-edge vortex generators and trailing-edge gurney flaps) was experimentally investigated at low Reynolds numbers for enhanced control of longitudinal dynamics of a two-dimensional NACA 4312 airfoil. The vortex generators are highly effective in controlling flow separation, delaying airfoil stall, and providing lift control at high angles of attack. The trailing-edge flaps provide a constant shift in the lift and drag curves for all angles of attack up to stall angle, and provide control forces much like a plane flap with reduced drag penalty. Furthermore, experiments conducted to investigate the spanwise influence of the actuators reveal that the interaction between the effects of individual trailing-edge gurney flaps is minimal. On the other hand, the interactions between the individual leading-edge vortex-generators are slightly more pronounced. These effects can be combined linearly to produce a desired net effect. A flow-control system employing distributed actuators can enable forces for maneuvering air vehicles without the use of conventional control surfaces.

V. Acknowledgment

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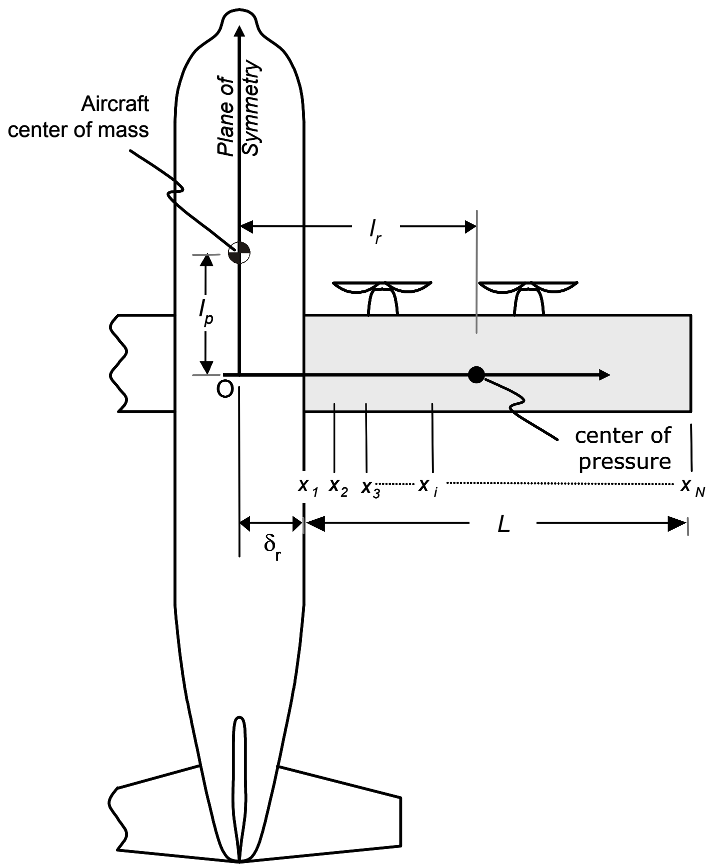


Figure 1. Vehicle schematic for Global Control System (GCS) design.[1]

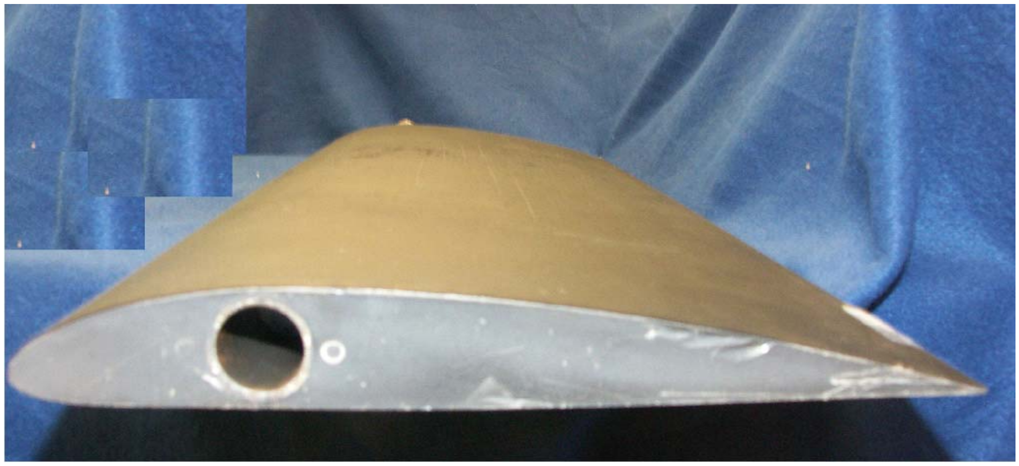


Figure 2. A photograph of the two-dimensional NACA 4312 airfoil used for wind tunnel testing.

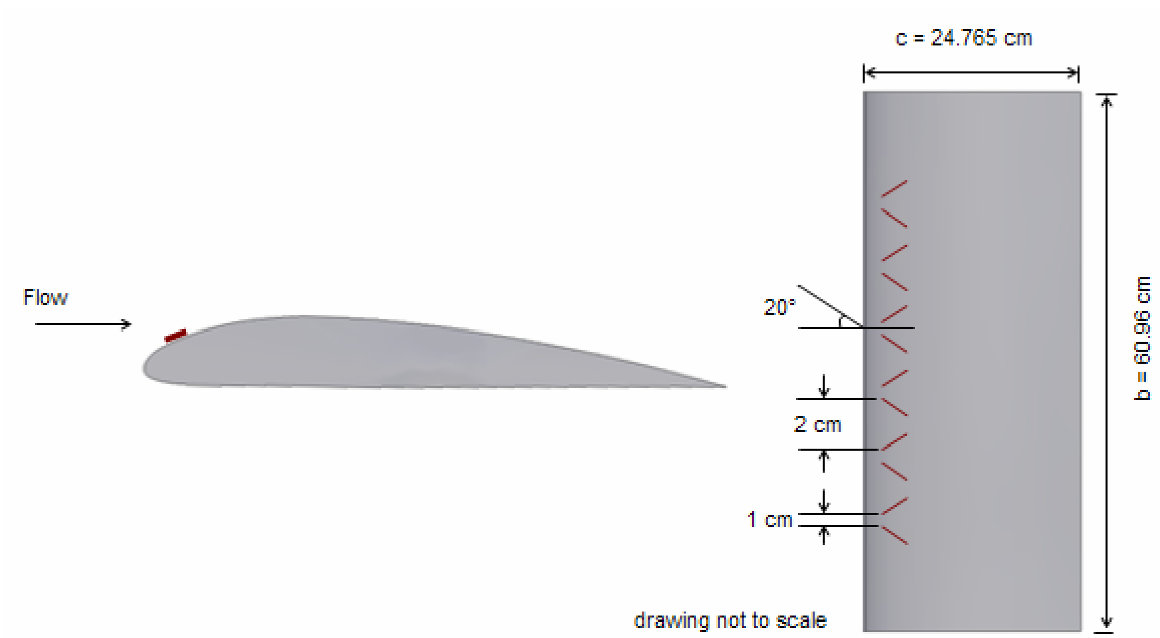


Figure 3. Vortex generators on the NACA 4312 airfoil.

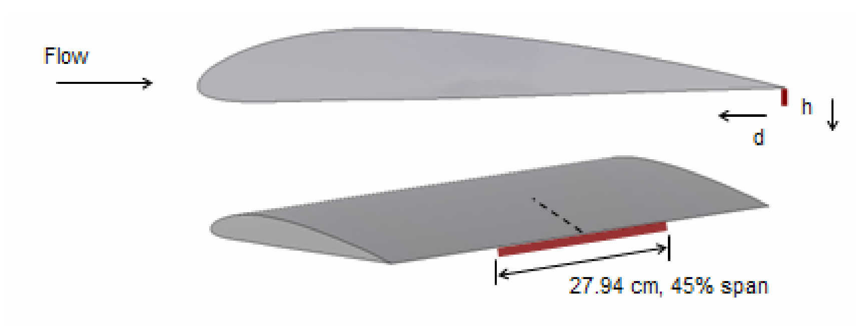


Figure 4. Gurney flap on the NACA 4312 airfoil.

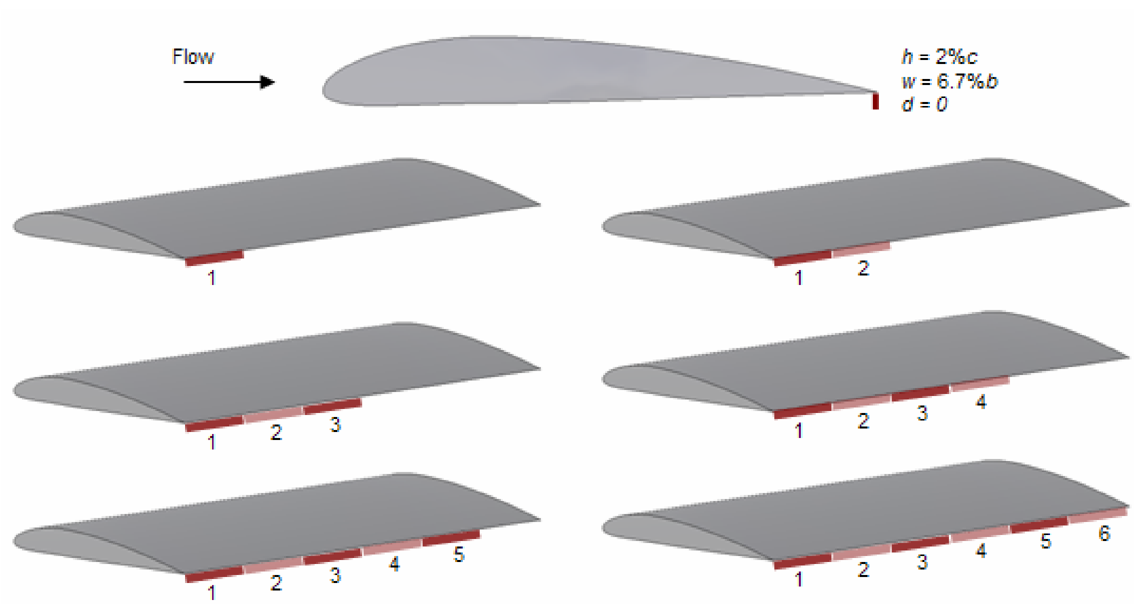


Figure 5. Distributed Gurney flap configurations tested on the NACA 4312 airfoil.

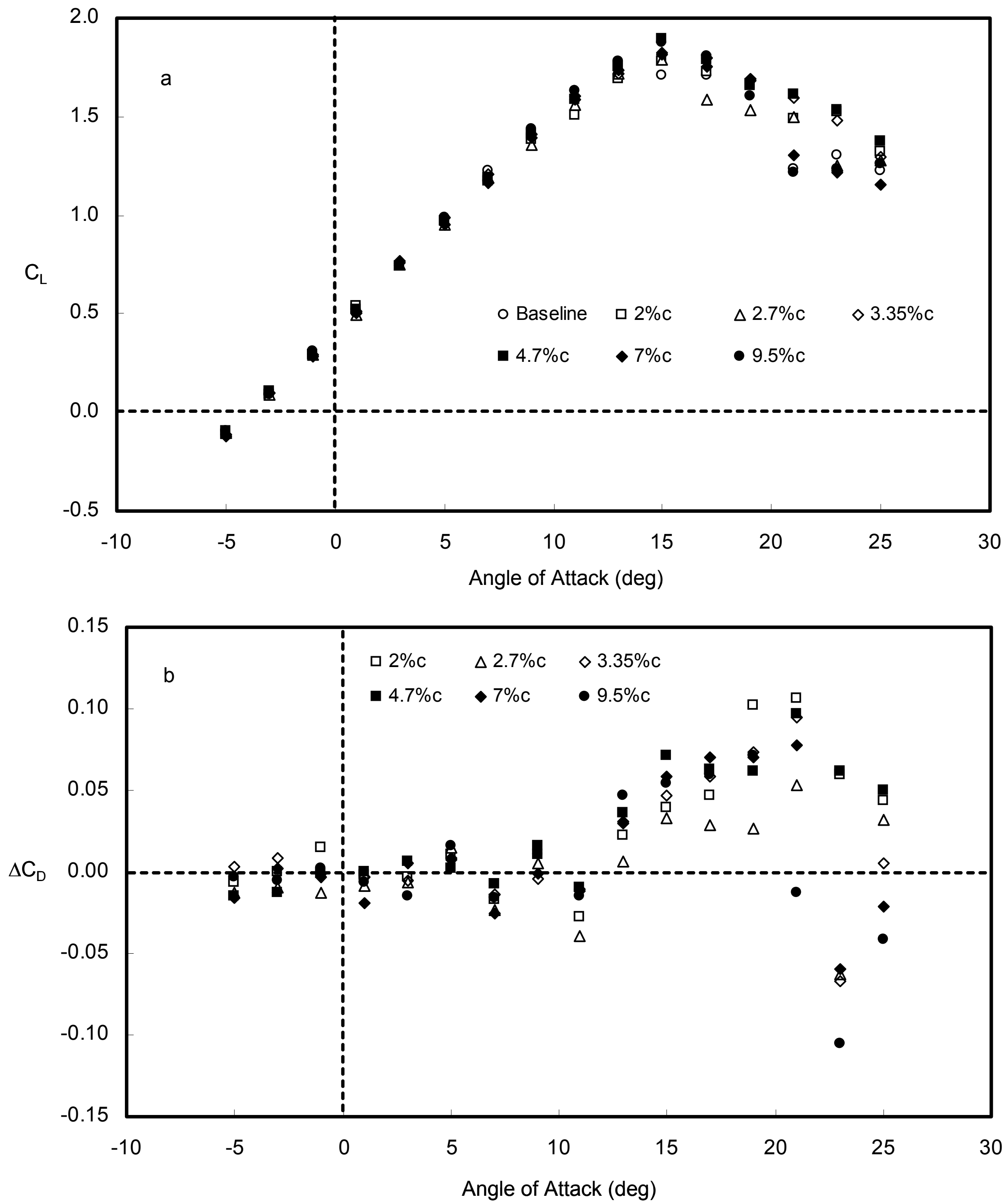


Figure 6. Overlay of effects of LEVGs on the lift and drag coefficients when tested at different chord locations. $Re_c = 3.15 \times 10^5$.

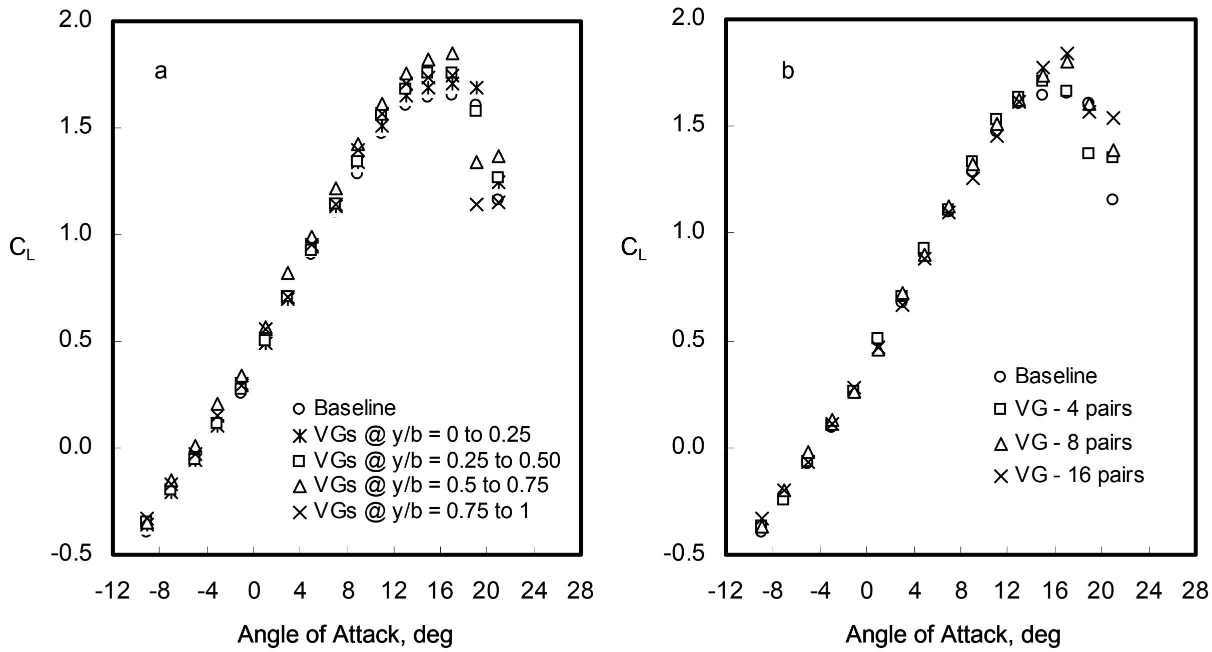


Figure 7. Effects of spanwise placement of the vortex generators and the number of VG pairs on the lift coefficient for α = -10 to 22 deg. Re_c = 2.6 × 10^5.

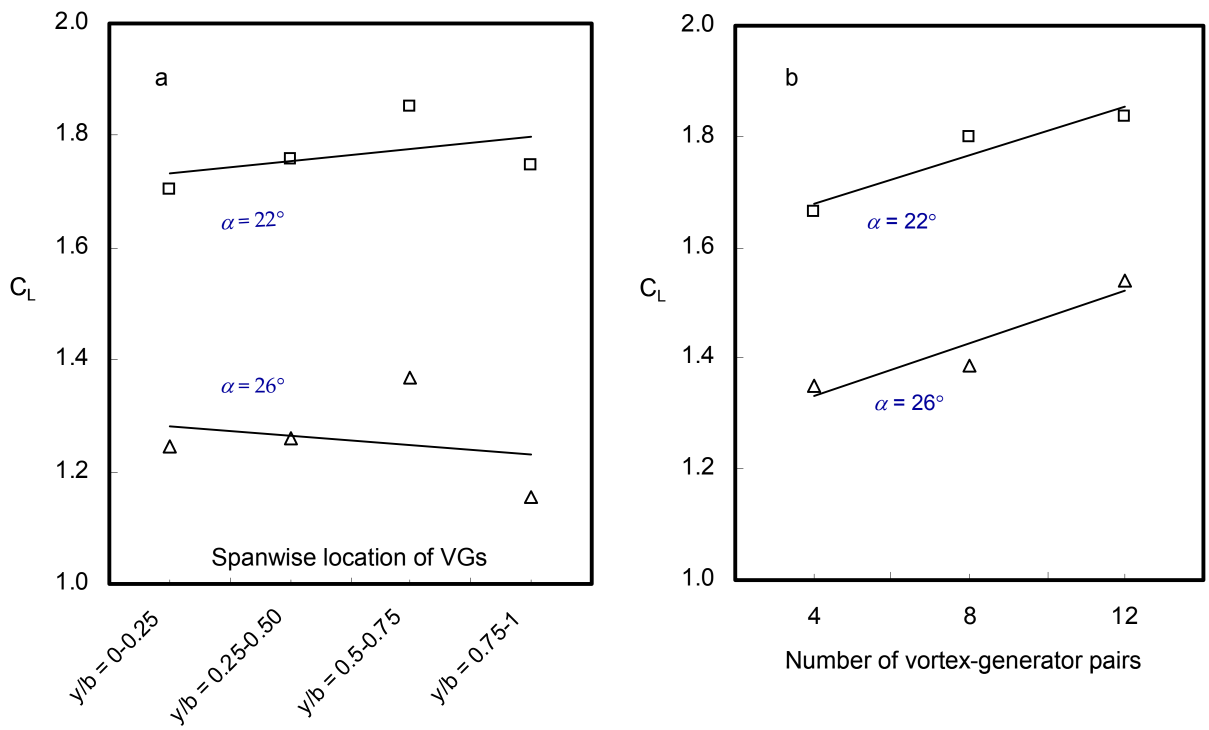


Figure 8. Effects of spanwise placement of the vortex generators and the number of VG pairs on the lift coefficient for α = 22 and 26 deg. Re_c = 2.6 × 10^5.

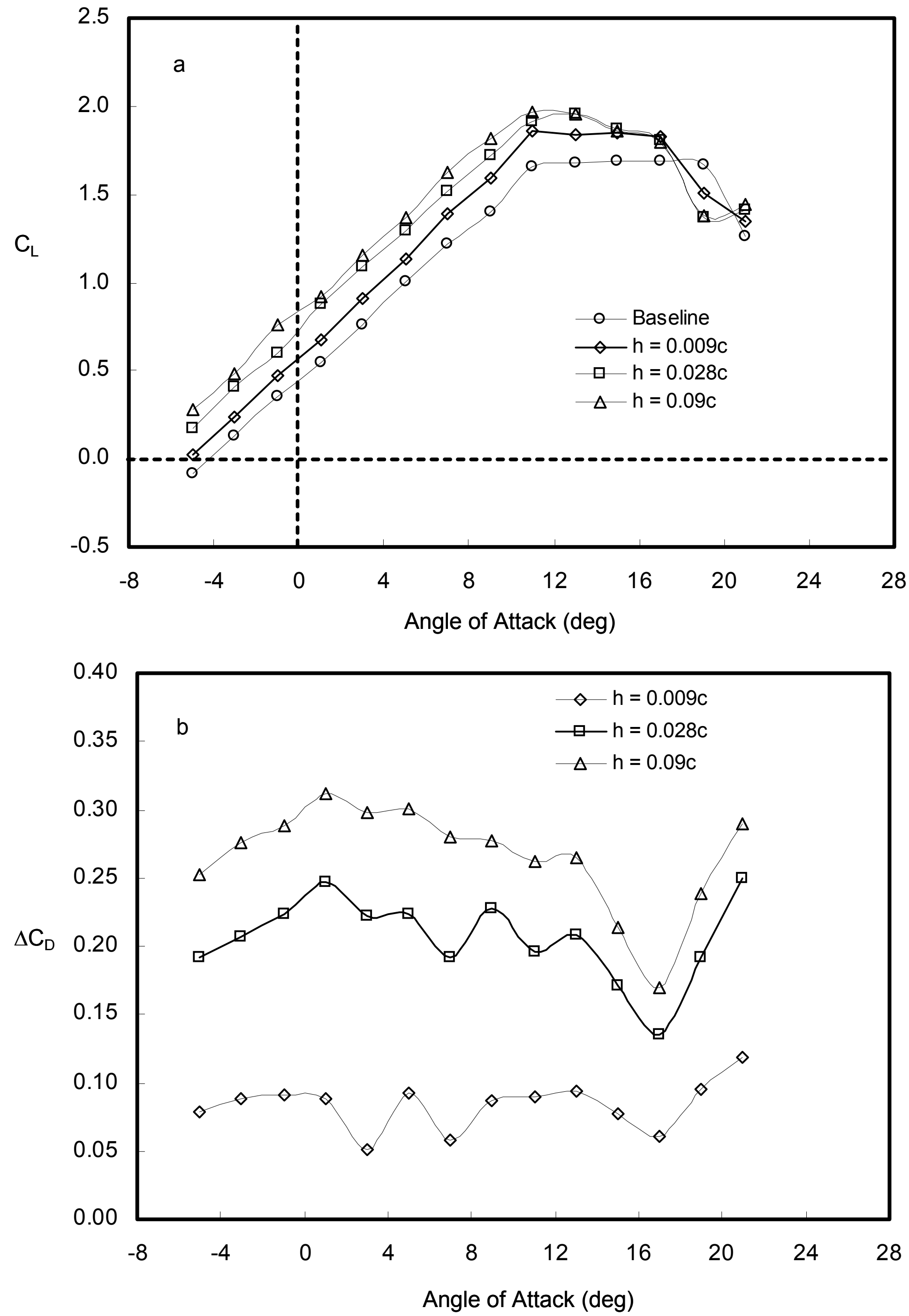


Figure 9. Overlay of changes in the lift and drag coefficients for different heights of the gurney flap for a NACA 4312 airfoil. $Re_c = 3.15 \times 10^5$.

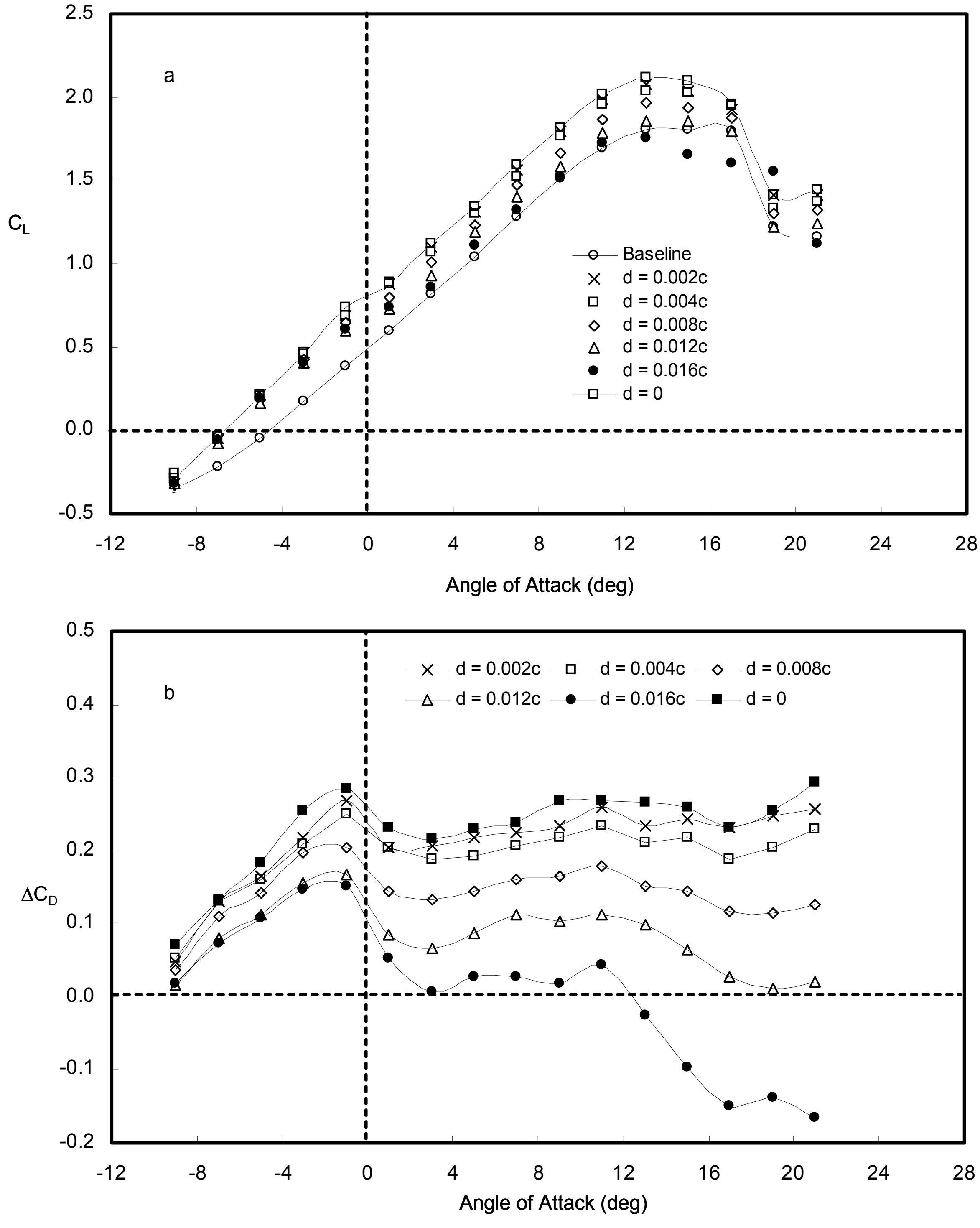


Figure 10. Overlay of changes in the lift and drag coefficients for different distances of the gurney flap measured from the trailing-edge for a NACA 4312 airfoil. $Re_c = 2.6 \times 10^5$.

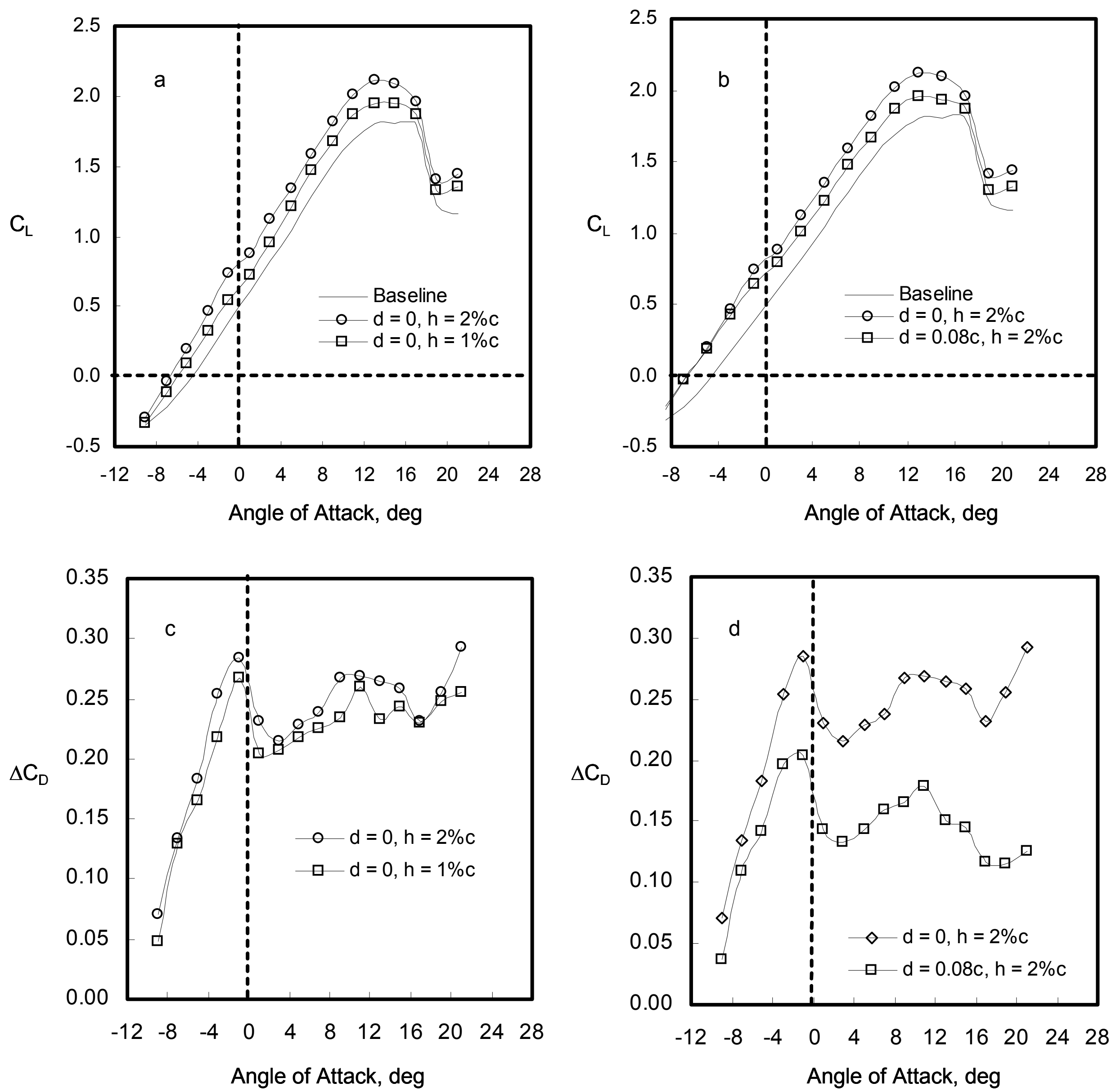


Figure 11. Effects of Gurney flap height and distance from the trailing-edge on the lift and drag coefficients as a function of angle of attack (right) on a NACA 4312 airfoil. $Re_c = 2.6 \times 10^5$.

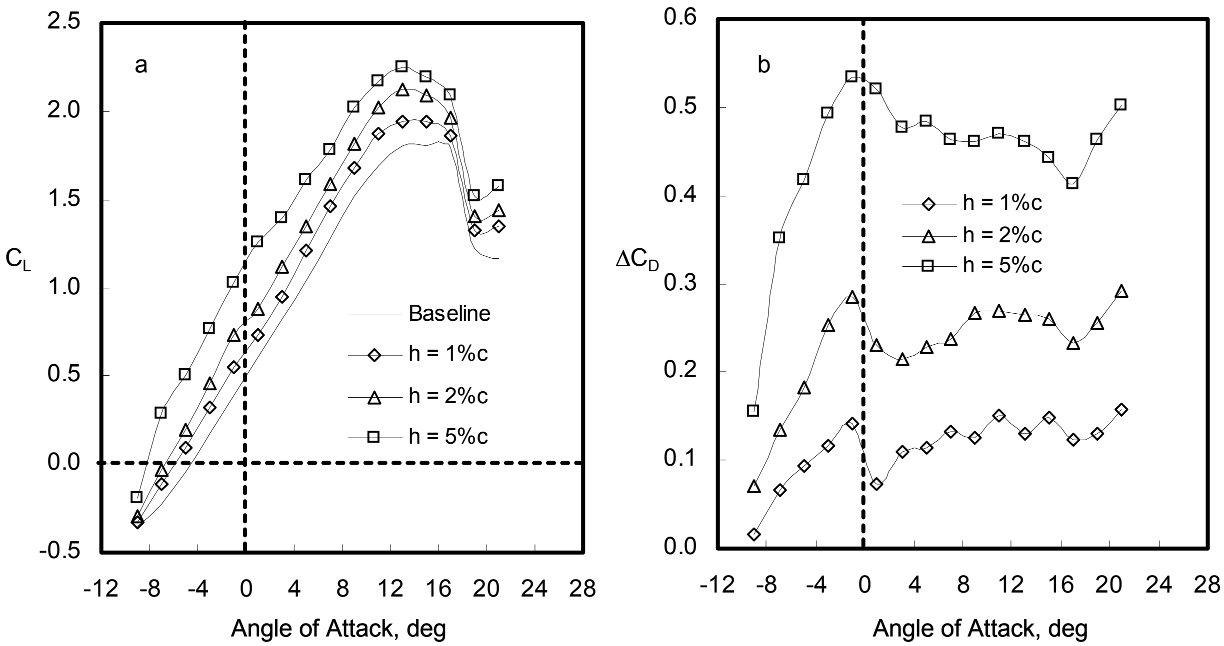
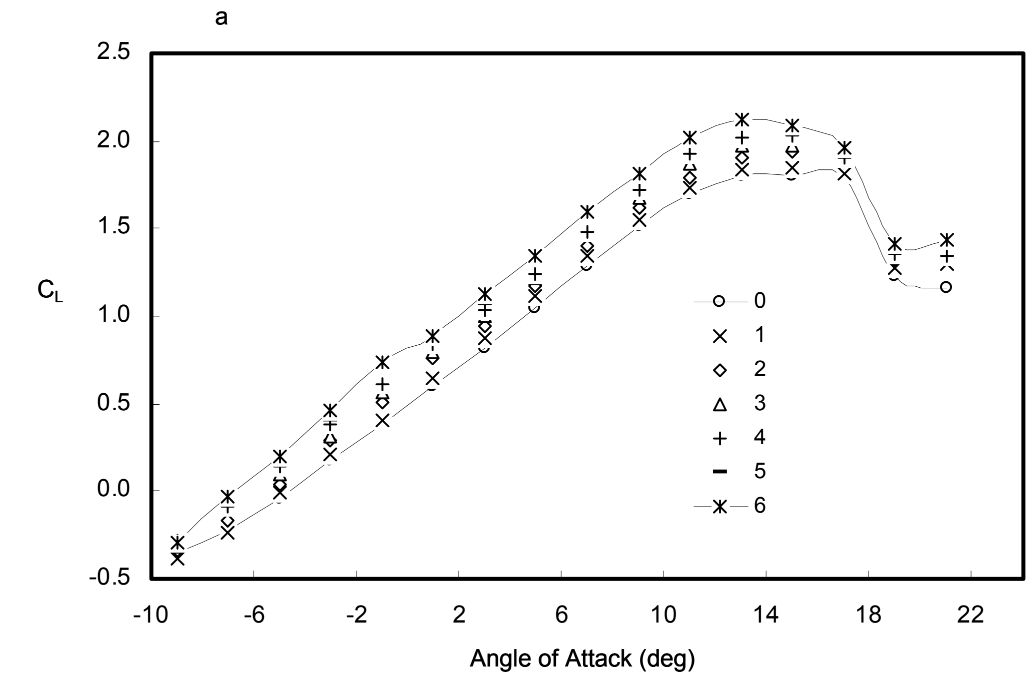


Figure 12. Effect of Gurney flap height on the lift and drag coefficients as a function of angle of attack on a NACA 4312 airfoil. $Re_c = 2.6 \times 10^5$.



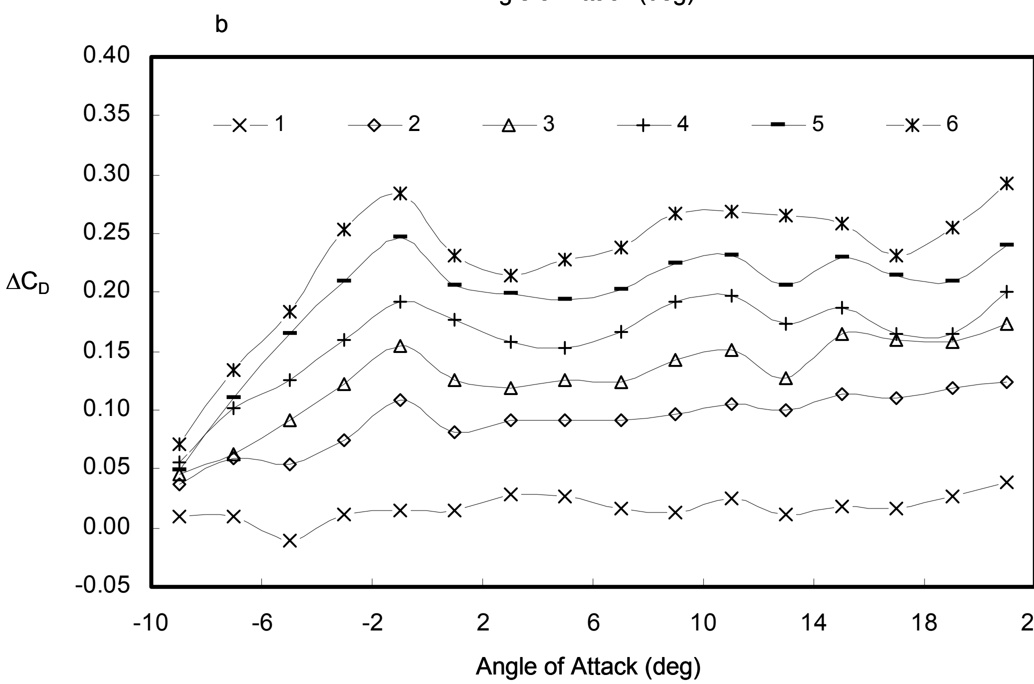


Figure 13. Effects of distributed Gurney flaps on the lift and drag coefficients as a function of angle of attack on a NACA 4312 airfoil. $Re_c = 2.6 \times 10^5$.

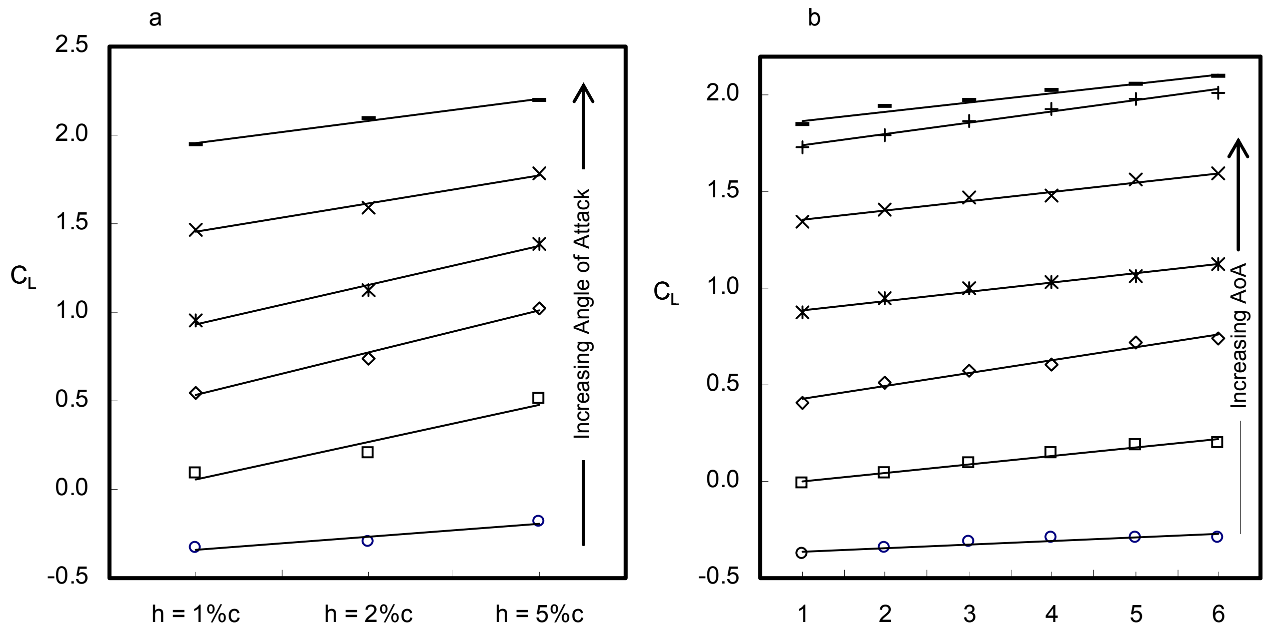


Figure 14. Effects of a single Gurney flap as a function of distance from the trailing-edge (left), and effects of distributed gurney flaps as a function of angle of attack (right) on a NACA 4312 airfoil. $Re_c = 2.6 \times 10^5$.

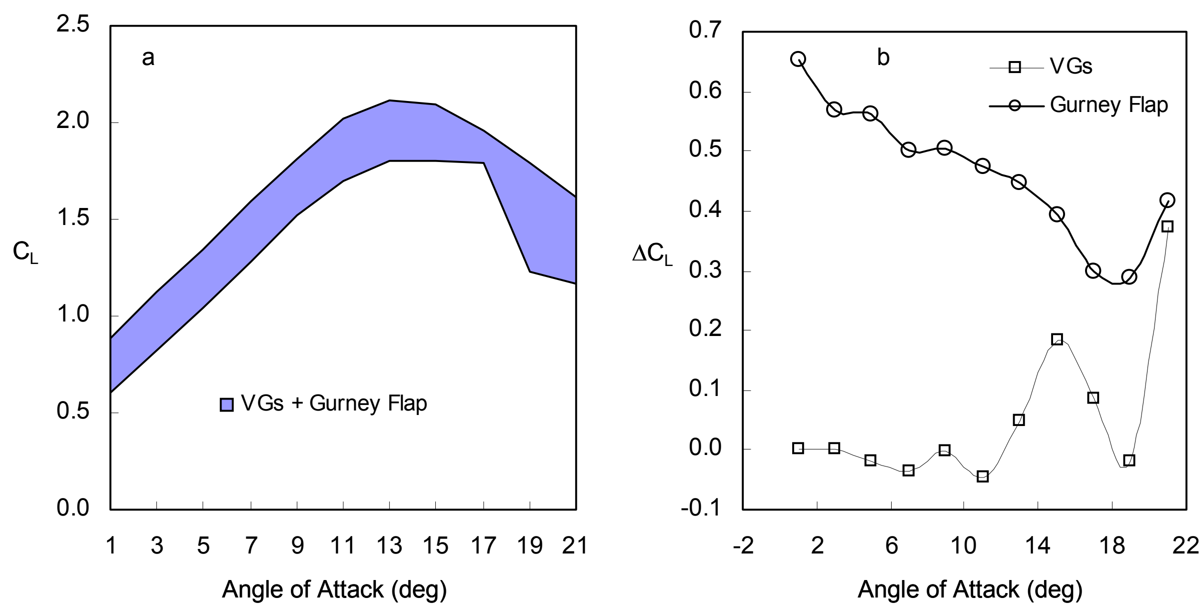


Figure 15. Combined effects of vortex generators and a gurney flap on a NACA 4312 airfoil. $Re_c = 2.6 \times 10^5$.